A NUMERICAL EXPERIMENT OF THE DEVELOPMENT OF THE ZONALLY SYMMETRIC NORTHERN SUMMER MONSOON.

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THESIS

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OF THE ZONALLY SYMMETRIC
NORTHERN SUMMER MONSOON

by

Wayne Lynn Patterson

June 1977

Thesis Advisor: C. P. Chang

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Numerical Experiment of the Development of the Zonally Symmetric Northern Summer Monsoon		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; June 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Wayne Lynn Patterson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE June 1977
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Monsoon
Zonally symmetric
Equilibrium temperature
Topography experiment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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DD FORM 1473, 1 JAN 73 (Page 1) EDITION OF 1 NOV 65 IS OBSOLETE S/N 0102-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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In both experiments, actual velocities are underestimated with the topography experiment providing the better results. Development of the monsoon was poor in both experiments, due mainly to the inability of the model's vertical resolution to simulate the extreme change in topography elevation and the unrealistic approach of a linear temperature change. Possible improvements for future studies are suggested.

A Numerical Experiment of the Development of the Zonally Symmetric Northern Summer Monsoon

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the
NAVAL POSTGRADUATE SCHOOL
June 1977

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The sudden onset of the northern summer monsoon has led to many theories as to the cause, one of these being a possible relation to the elevated Tibetan highland that dominates the area.

Using a zonally symmetric numerical model driven by a specified equilibrium heating function, two experiments are conducted. The first experiment integrates the model over a 180-day period on a flat earth, linearly changing the equilibrium temperature from January to July. The second experiment repeats the first except for the inclusion of the topography of 85°E longitude.

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ACKNOWLEDGEMENTS

The author wishes to thank Professor C. P. Chang for his invaluable assistance and guidance as thesis advisor, Professor R. T. Williams for his assistance in solving the numerical complications that arose, and the personnel on the evening and weekend shift at the W. R. Church Computer Center for their generous support in carrying out the lengthy numerical computations. Much appreciation is extended for the patience and understanding of my wife which contributed vastly to the successful completion of this work.

I. INTRODUCTION

Monsoons, meaning "season" from the Arabic, are complex, seasonally dependent weather systems covering the entire tropics and subtropics. The northern summer monsoon begins in June and is characterized by a surface monsoon trough over India, with an upper level anticyclone over the Tibetan plateau. To the south of this Tibetan anticyclone, near 10°N to 15°N, is a strong easterly jet stream which encompasses almost the entire tropics, the maximum of the jet stream velocities being centered at approximately 85°E longitude.

Of interest to meteorologists for many years has been the rapidity with which the onset of the monsoon activity occurs. During the winter months, the Asia continent is under the influence of a subtropical westerly jet stream at the upper levels. Over a very brief period of time, measured in days, the westerly jet stream migrates toward more northern latitudes and is replaced in the tropics by the tropical easterly jet stream. Coupled with this replacement is the surface monsoon trough development and its associated surface southwesterly winds, winds laden with moisture from the oceans. These southwesterly winds cause widespread rainfall as they reach the southern Asia continent.

The need to understand the sudden onset of the summer monsoon has led to many theories among meteorologists. Yin (1949) has proposed that this onset, as represented by the sudden

replacement of the westerly jet by the easterly jet in the tropics, may be related in some way to the effect of the Tibetan highlands, an elevation that is very striking in nature.

The purpose of this study is to examine such a possibility by using a numerical model to simulate the development of the summer monsoon with different experiments. For the first experiment, a zonally symmetric January steady state condition on a flat earth is obtained. Starting from this condition, the model is integrated for 180 days with the mean thermal condition changing from January to July. The final state represents a July steady state condition. In the second experiment, the distribution of topography along 85°E, which is near the center longitude of the Tibetan highland, is included in the model. The 180-day integration is repeated.

It is hoped that by comparing the results of these two experiments, some understanding of topographical effects upon the evolution of events that leads to the development of the summer monsoon may be obtained.

II. MODEL AND PROCEDURE

A. BASIC MODEL

In this study, the model formulated by Monaco and Williams [1975] is used. This model uses the primitive equations in spherical coordinates with "sigma" as the vertical coordinate. The horizontal distribution of variables is on a 4-degree resolution. The model is made zonally symmetric by removing all zonal variations. The troposphere is divided into seven equally spaced "sigma" levels with three main reporting levels. The sigma coordinate is defined as:

$$\sigma \equiv \frac{p - p_t}{\pi} \quad , \qquad (2.1)$$

where p is the pressure of the sigma level, p_t is the height of the constant tropopause which is set at 100 mb, and π is the terrain pressure defined as:

$$\pi \equiv p_s - p_t \quad , \qquad (2.2)$$

where p_s is the surface pressure.

Time integration is comprised of continuous sections of one Matsuno and four leapfrog steps with time increments of 6 minutes. All data for this study are interpolated to constant pressure surfaces of 250 mb, 500 mb, and 850 mb.

B. SPECIFICATION OF HEATING AND TOPOGRAPHY

The model is driven by a heating function, H, which continuously adjusts the model atmosphere temperature to a specified equilibrium temperature, T*, using the following formula:

$$H = - \left[\frac{T - T^*(y,\sigma)}{t} \right] , \qquad (2.3)$$

where T is the model atmosphere temperature and t is a specified adjustment time, set at two days for this study.

In the no-topography experiment, the equilibrium temperatures for January and July are extracted from observations of Palmen and Newton [1969] for the January and July climatology (Figures 1 and 2, respectively). The dashed lines indicate the horizontal sigma levels used in obtaining the temperatures, in this case assuming the model levels to be 250 mb, 550 mb, and 850 mb.

Because the temperatures in July at 85°E are considerably warmer than the zonally averaged temperatures, the equilibrium temperature for July is modified by the addition of a departure from the zonal mean, at 85°E, as observed by Krishnamurti [1971] and shown in Figure 3. At the 250 mb level, the full departure is added to the mean temperature. At the 550 mb level, 50 percent of the departure is added. At the 850 mb level, 20 percent of the departure is added to the mean temperature.

In the topography experiment, topography as a function of latitude is shown in Figure 4. It is introduced through a gradual change in the surface geopotential, ϕ_s, as given by the following formula:

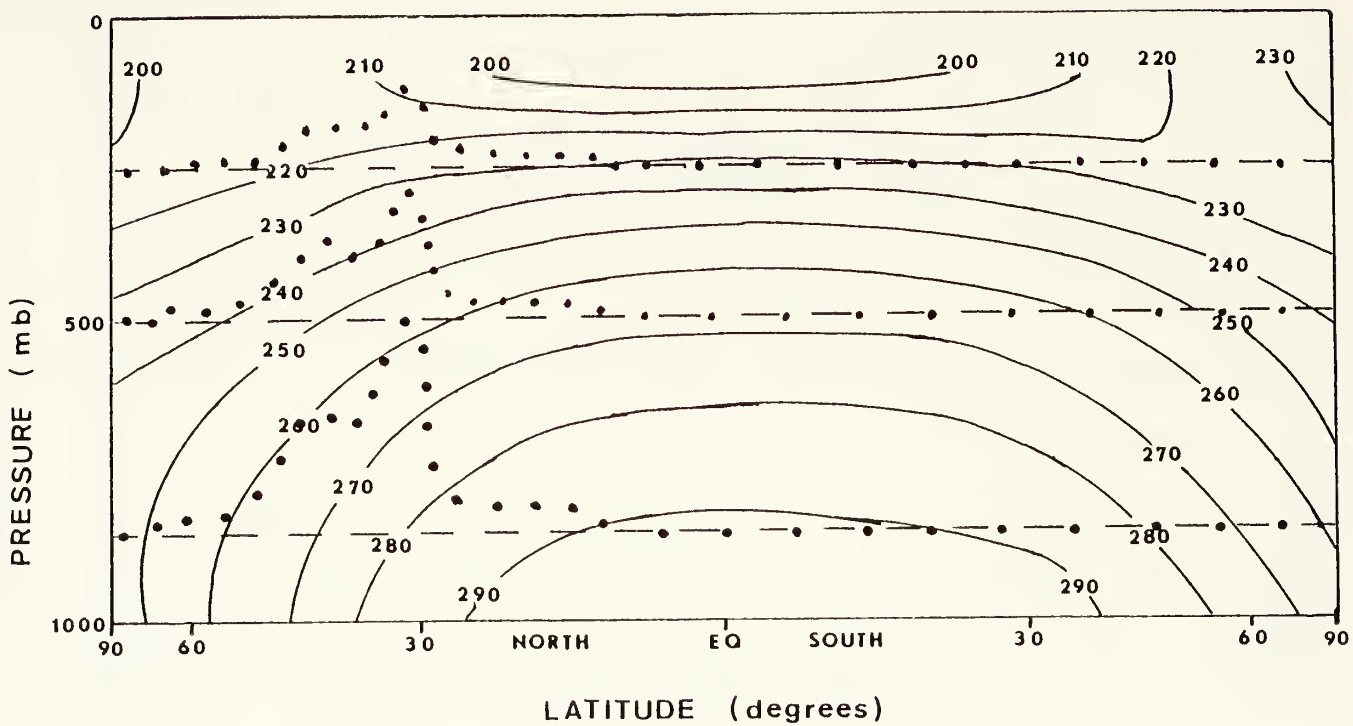

Figure 1: Zonal mean temperature for the month of January.

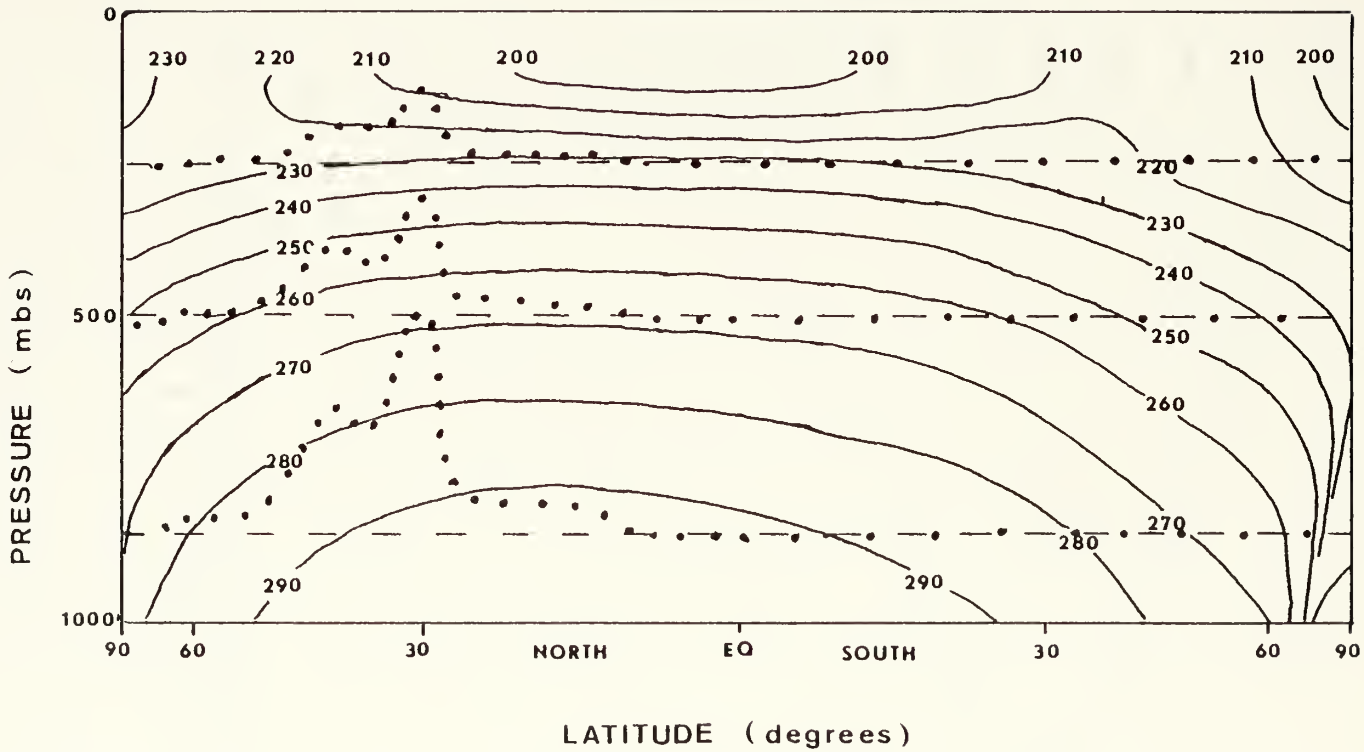

Figure 2: Zonal mean temperature for the month of July.

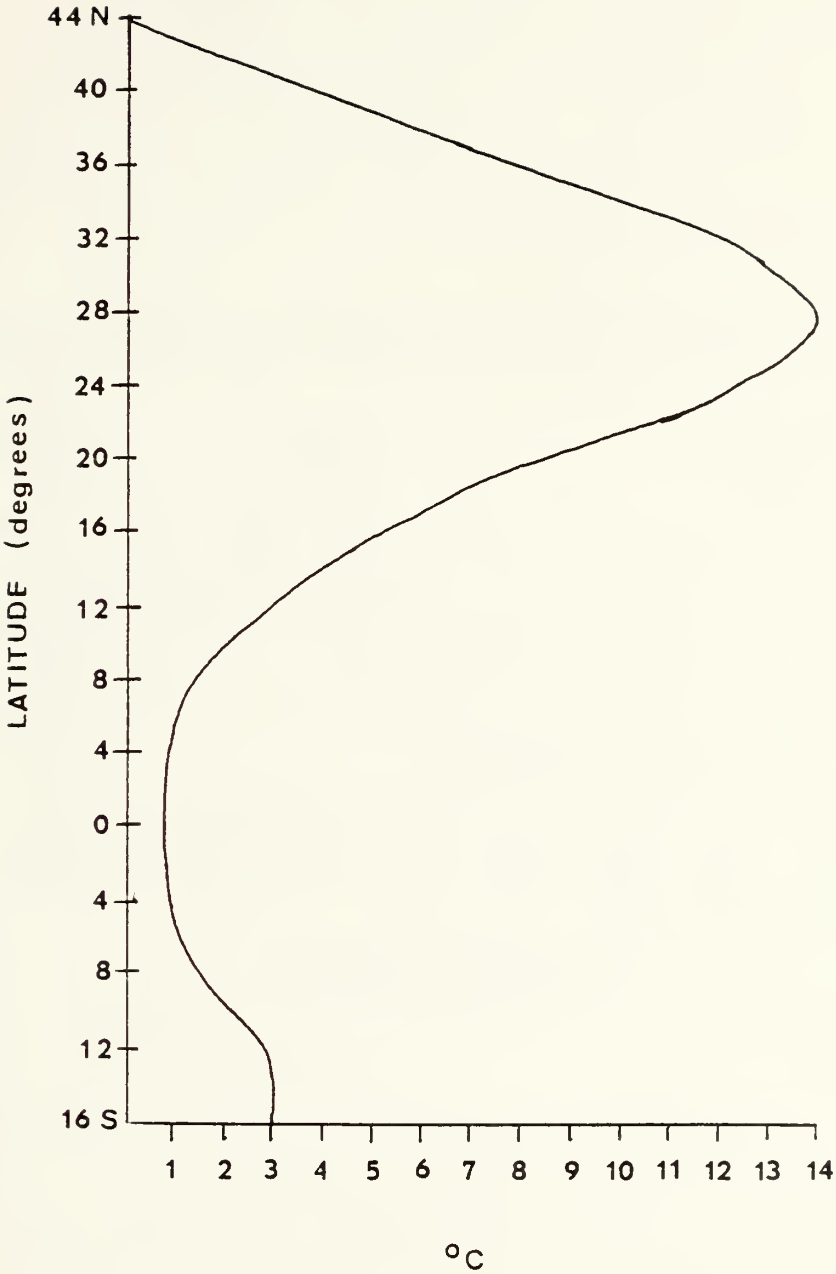

Figure 3: Deviations from the zonal mean July temperature at 85°E longitude.

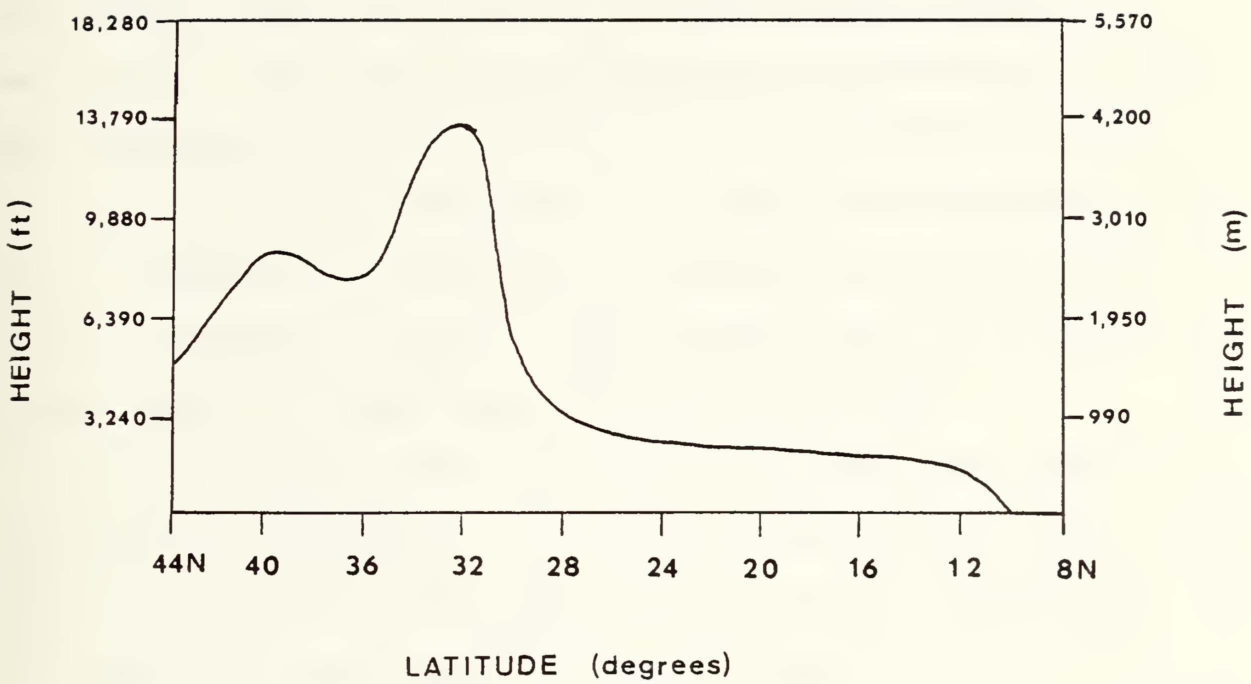

Figure 4: Topography elevation at 85°E longitude.

$$\phi_s = \phi_f \left(\sin^2 \left(\frac{\pi t_e}{2+p} \right) \right) . \qquad (2.4)$$

Here, ϕ_f is the specified final surface geopotential value; t_p is the total amount of time required for mountain building, specified as 24 hrs for this study; and t_e is the number of incremental changes to occur within the mountain building item, specified as 48 hrs for this experiment.

The gradual build-up of the topography is to avoid the undesirable numerical shock of a sudden change invariable magnitudes. The same January equilibrium temperature for the no-topography experiment is used in this experiment before the introduction of topography, but after the topography is fully developed the temperature specified along the dotted lines in Figure 1 is used. These curves, which are initial sigma levels, are patterned after the topography.

The July equilibrium temperature for this experiment is extracted from Figure 2, following the same dotted lines. Modification of the July temperature is again accomplished by adding the same deviation from the mean as used in the no-topography experiment.

C. NO-TOPOGRAPHY EXPERIMENT

In this experiment, pressure levels are initialized at standard atmospheric values with all velocities being zero. The initial temperature is specified as the January equilibrium temperature as shown in Figure 1. The model is started and allowed to run for a period of 90 days, sufficiently long to establish a quasi-steady state condition.

The integration is continued from this steady state condition and allowed to run for a period of another 180 days. Throughout this run, the equilibrium temperature is continuously changed, by a simple linear interpolation, to reach the equilibrium temperature of July.

At the end of the 180-day run, the integration is allowed to continue for an additional 90 days with the July equilibrium temperature remaining fixed in order to achieve a quasi-steady state condition for July.

There is no significant difference between the circulation patterns at the end of the 180-day run and those at the end of the additional 90 days using constant July temperatures. Thus, it is apparent that the model adjusts well to the equilibrium heating function and any day within a particular simulation period may be considered to represent an instantaneous quasi-steady state condition.

D. TOPOGRAPHY EXPERIMENT

The procedure for this part of the experiment is similar to the no-topography case except for the introduction of topography. To compensate for the mass changes due to the volume of atmosphere change, the surface pressure is specified as 860 mb, a figure experimentally determined to produce an over ocean surface pressure of 1013 mb.

The same January equilibrium temperature used for the no-topography experiment is held fixed and the model is integrated for a period of 45 days, allowing the model to adjust to the artificially low initial surface pressure. At this point,

the topography is introduced as previously discussed and the equilibrium temperature is readjusted to conform with the topography sigma levels as shown by the dotted line in Figure 1. An additional 45 days is allowed after the introduction of topography and January temperature change to achieve a January steady state.

From this steady condition, the integration is allowed to proceed for 180 days, again allowing the equilibrium temperature to change linearly from January to July, the July temperature being obtained as previously discussed.

The July equilibrium temperature is again held fixed and the model is allowed to continue for an additional 90 days. There is again no significant difference between the wind patterns at the end of the 180-day integration and the additional 90-day run.

III. RESULTS

The principal circulation features of interest in this study are the Tibetan high and the tropical easterly jet stream. The simulation of the development of these features by the model are compared with observations at 85°E, mainly those of Sadler [1975].

A. SIMULATED CIRCULATIONS IN JANUARY AND JULY

1. No-Topography Experiment

The January steady state condition without the inclusion of topography is represented by the zonal wind as a function of latitude and elevation in Figure 5. The zonal wind at 250 mb as a function of latitude is compared with that observed by Sadler at 200 mb in Figure 6. The observed westerly flow occupies the region north of approximately 14°N with a well defined jet core at 32°N. The maximum velocity in this core is, on the average, 44 m sec^{-1}. The model produces a broad and weak westerly flow to northward of 4°N. There is a definite lack of a well defined, sharp jet maximum, the maximum velocity being 21.6 m sec^{-1} at 40°N. At all latitudes, the velocities are grossly underdeveloped.

The July steady state condition is represented by the zonal wind as a function of latitude and elevation in Figure 7. The zonal wind at 250 mb as a function of latitude is compared with Sadler's observation at 200 mb in Figure 8. The replacement of the westerly jet stream by the tropical

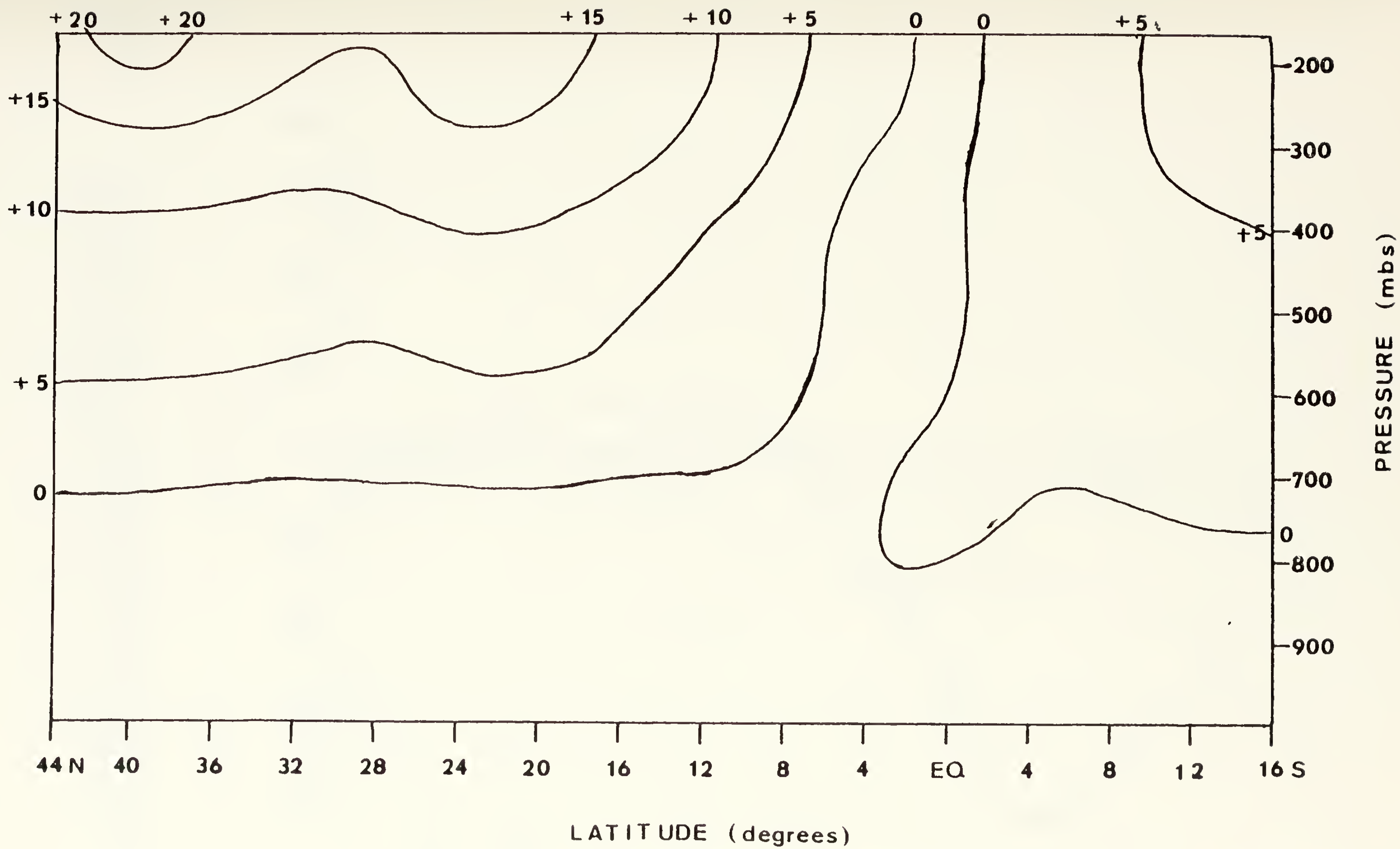

Figure 5: Simulated zonal wind for January, no topography. Units are m sec^{-1}.

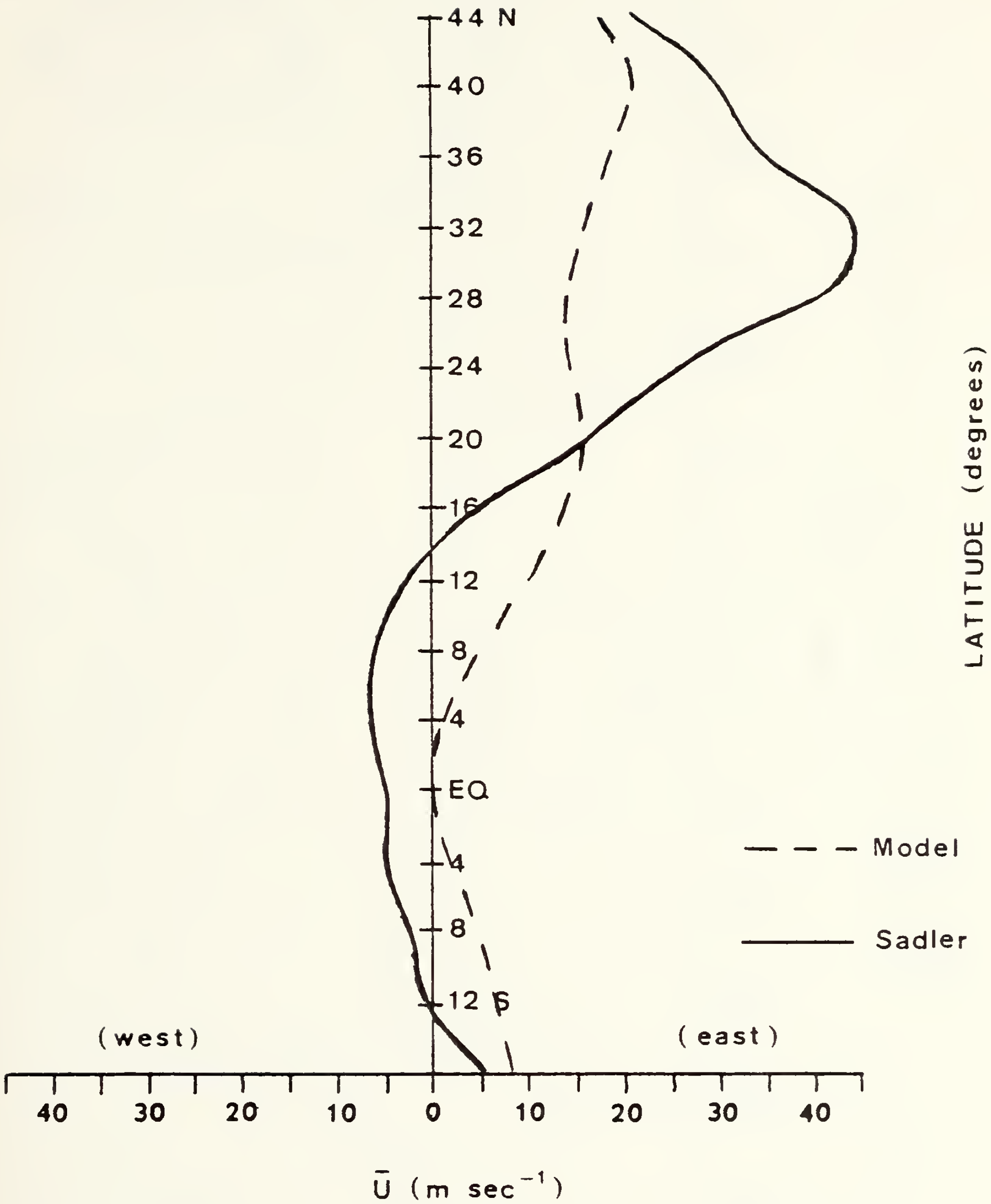

Figure 6: Simulated zonal wind at 250 mb vs. observed zonal wind at 200 mb for January, no topography. Units are m sec^{-1}.

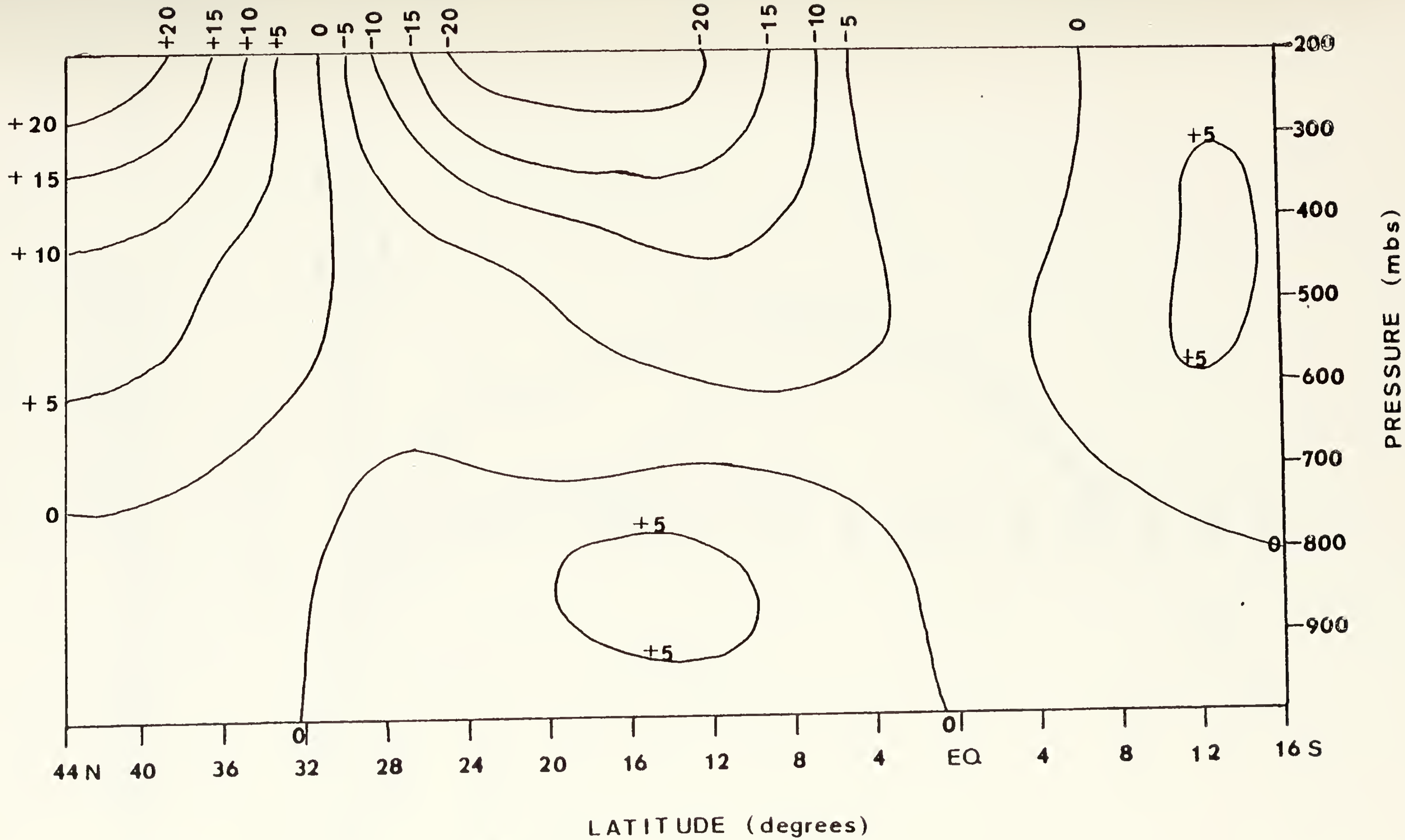

Figure 7: Simulated zonal wind for July, no topography. Units are m sec^{-1}.

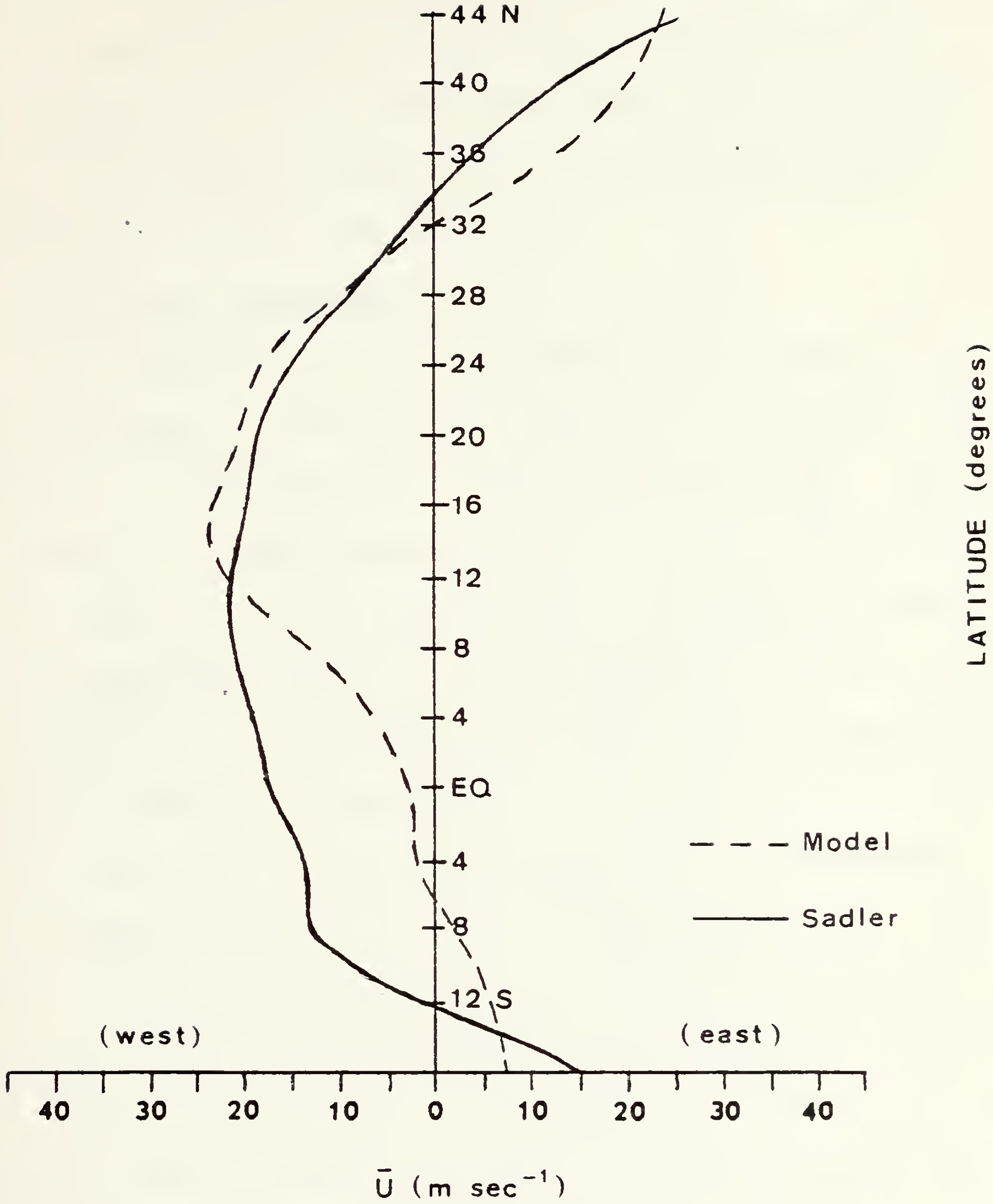

Figure 8: Simulated zonal wind at 250 mb vs. observed zonal wind at 200 mb for July, no topography. Units are m sec^{-1}.

easterly jet is quite evident in both data. The observed easterly jet axis is centered at 12°N with a maximum velocity of 22 m sec^{-1}. In this experiment, the model produced a more realistic result than the January state. The simulated tropical easterly jet is clearly developed with a core axis at 16°N. The maximum velocity in the core is 23 m sec^{-1}, in close agreement to the observed value.

2. <u>Topography Experiment</u>

The January steady state condition with the inclusion of the topography is displayed in Figure 9 which gives the zonal wind as a function of latitude and elevation. The zonal wind at 250 mb is again compared with Sadler's observation at 200 mb in Figure 10. The underestimate of winds, a problem in the no-topography case, is still evident but not to such an extreme degree. For example, at 32°N, the no-topography value of 16 m sec^{-1} is increased to 26 m sec^{-1}. It is still below the 44 m sec^{-1} observation, however. The simulated pattern changes markedly from the no-topography case. The simulation shows a clearly bimodal distribution with jet stream cores of 25 m sec^{-1} at 20°N and 26 m sec^{-1} at 32°N, the latter coincides with the observed latitude of the westerly jet core. The latitude band between these two jet cores contains the vertical face of the model topography.

The July steady state condition is shown in Figure 11 by the zonal wind as a function of latitude and elevation. Figure 12 gives the comparison of the simulated zonal wind at 250 mb and the observed zonal wind at 200 mb by Sadler as

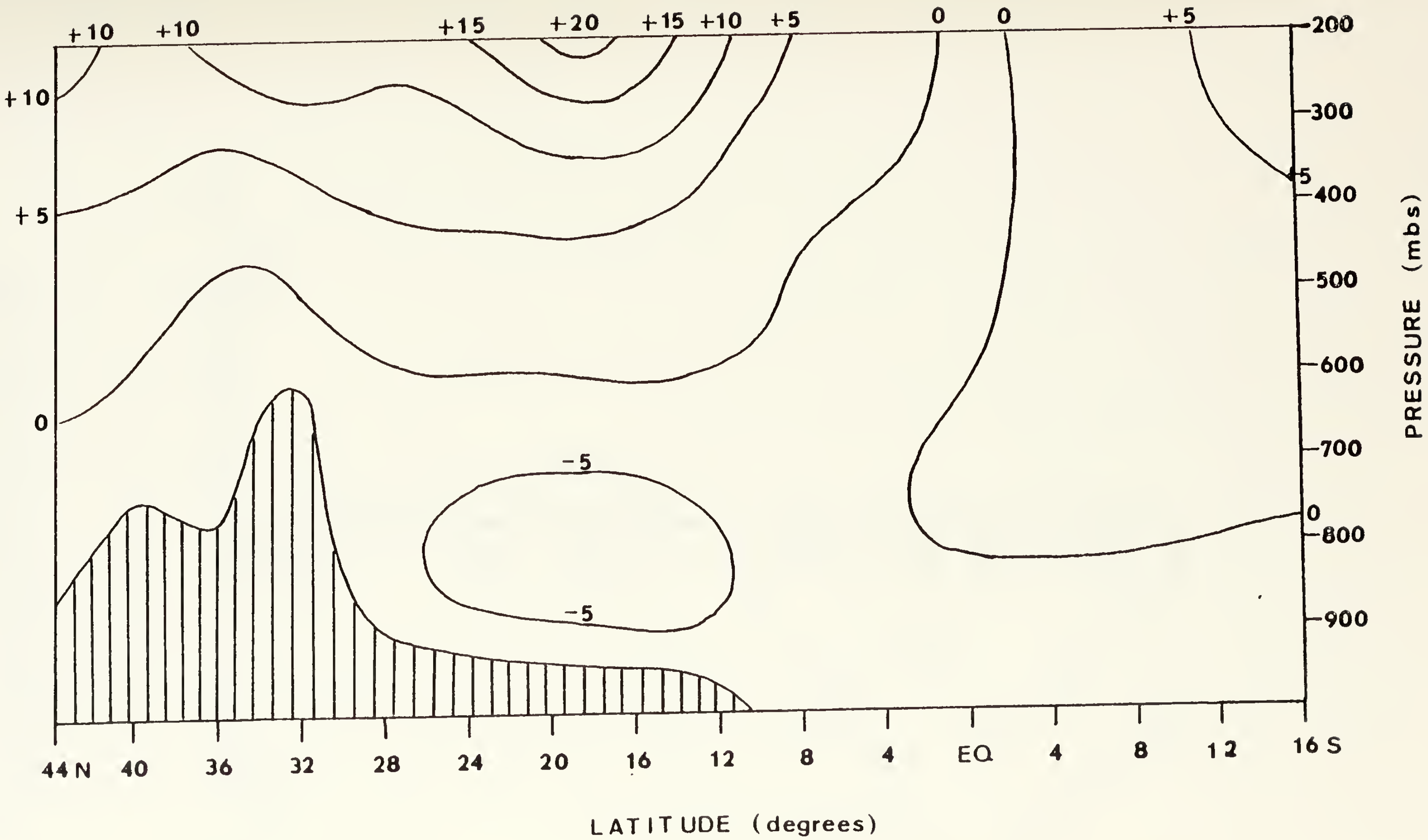

Figure 9: Simulated zonal wind for January with topography. Units are m sec^{-1}.

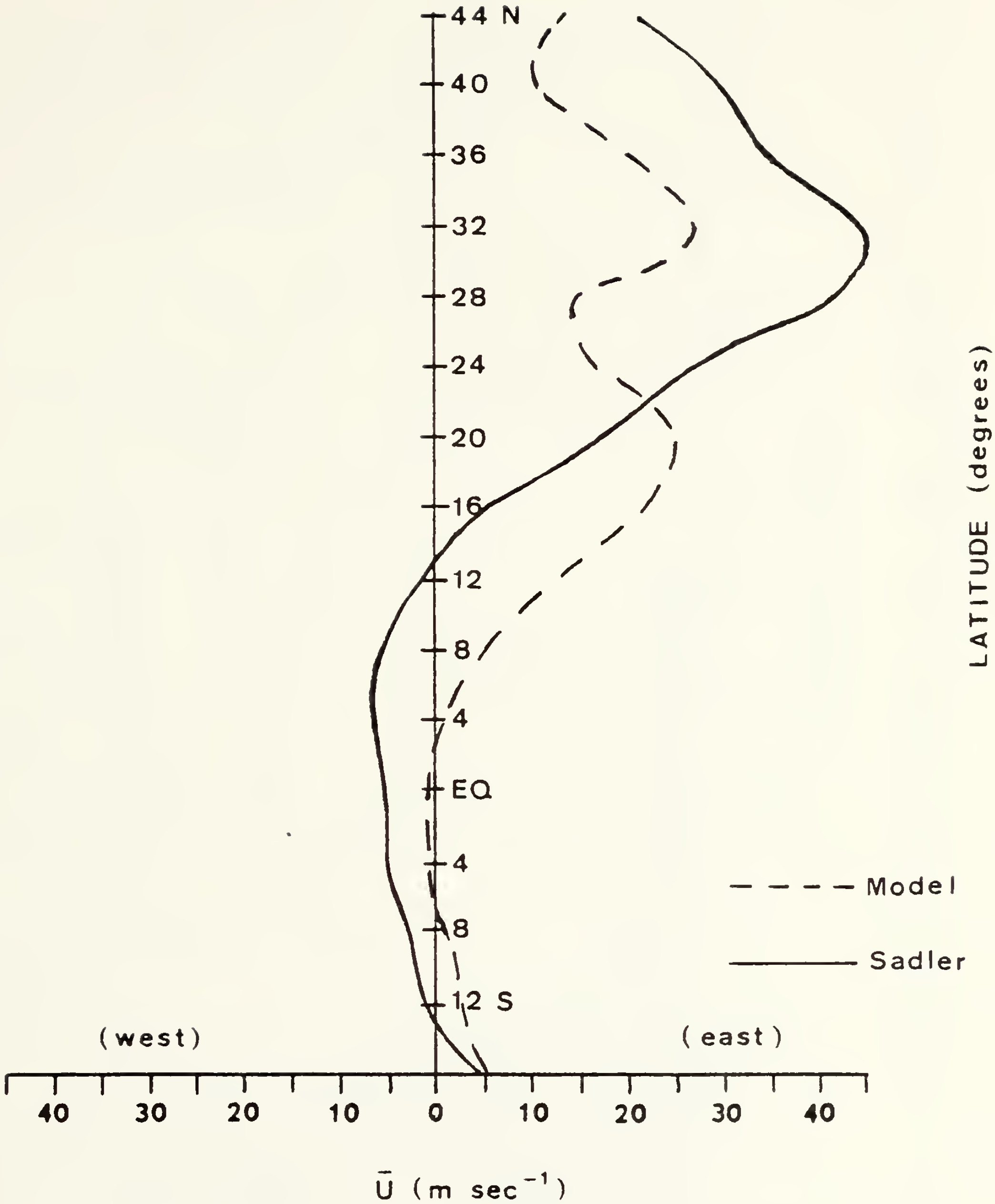

Figure 10: Simulated zonal wind at 250 mb vs. observed zonal wind at 200 mb for January with topography. Units are m sec^{-1}.

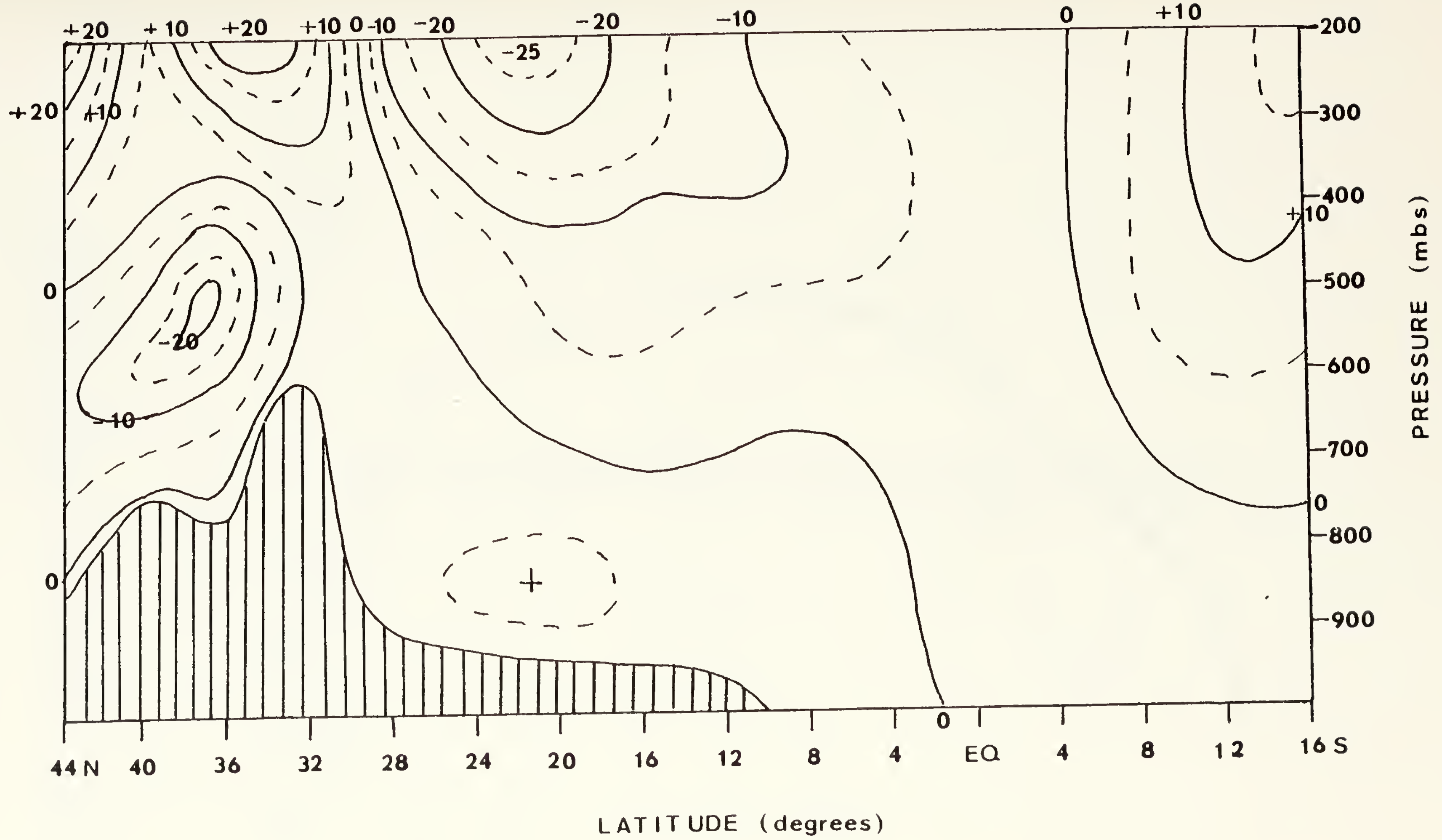

Figure 11: Simulated zonal wind for July with topography. Units are m sec^{-1}.

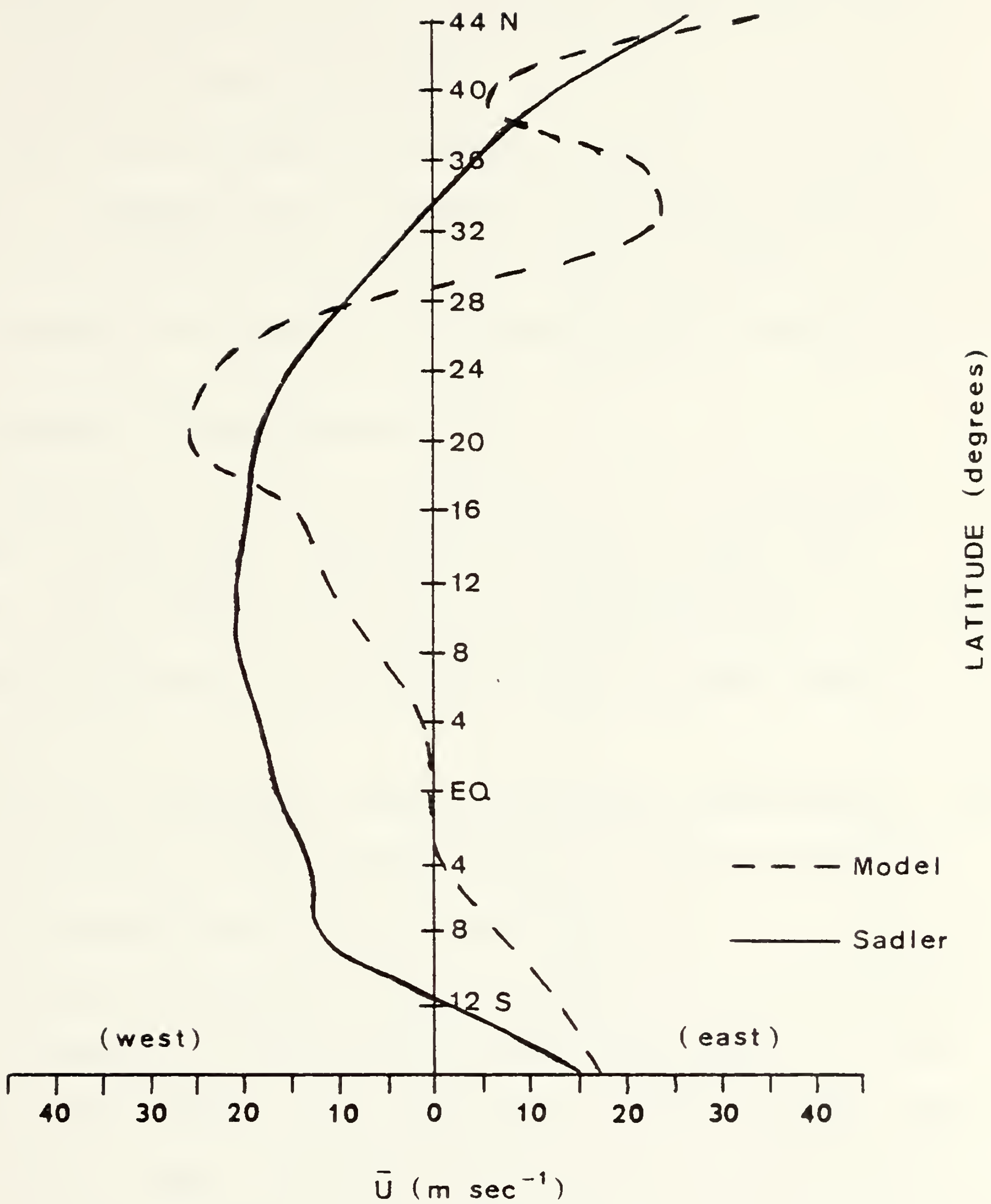

Figure 12: Simulated zonal wind at 250 mb vs. observed zonal wind at 200 mb for July, with topography. Units are m sec^{-1}.

a function of latitude. In this case, the near match in the velocities in the latitudes of the tropical easterly jet has diminished somewhat. The jet core is shifted north to 20°N and the velocity is 27 m sec^{-1}, an overestimate from observation by approximately 7 m sec^{-1}.

There are no good observational data at 85°E longitude with which to compare the 500 mb and 850 mb flow simulations. The patterns are consistent with the 250 mb patterns, however, as to placement of features and intensities of circulations.

B. DEVELOPMENT OF THE MONSOON FLOW

The zonal wind at 250 mb produced in the no-topography experiment is shown as a function of latitude and time in Figure 13. The zonal wind at 250 mb produced in the topography experiment is shown as a function of latitude and time in Figure 14.

In both the topography and no-topography experiments, the seasonal reversal in the zonal wind at the 250 mb level is completed gradually over the six-month period.

The tropical easterly jet first appears at approximately 12°N in mid-March for the no-topography experiment. In the topography experiment, it is developed at approximately 20°N in early March, thus a shift of the jet axis to the north by 8 degrees of latitude with the introduction of topography is produced. This displacement in the core is not observed and thus must be considered incorrect. In the real atmosphere, the appearance of the tropical easterly jet actually begins in mid-May and is centered at approximately 12°N.

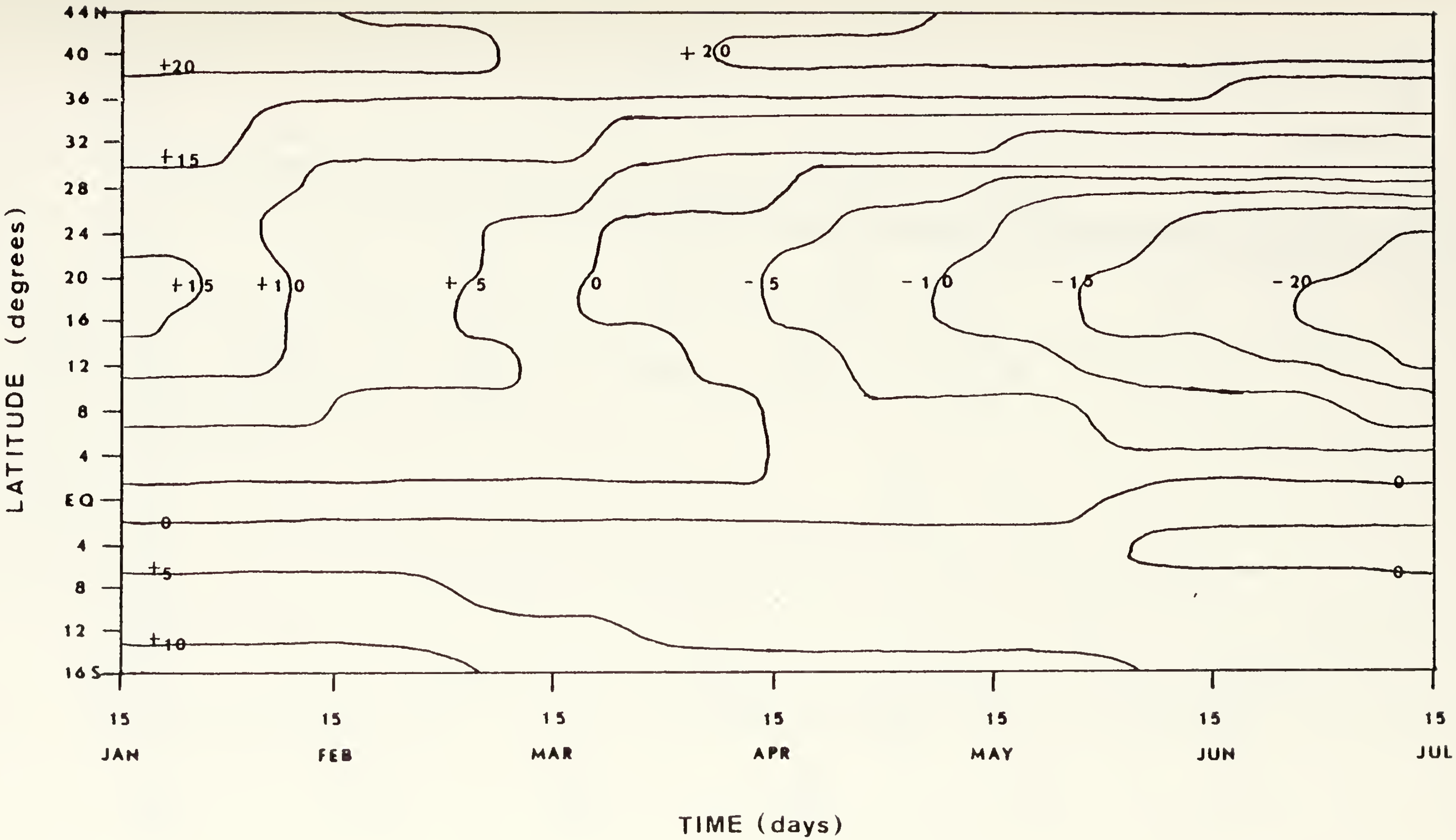

Figure 13: Latitude-time section of zonal wind (m sec^{-1}) for the no-topography experiment.

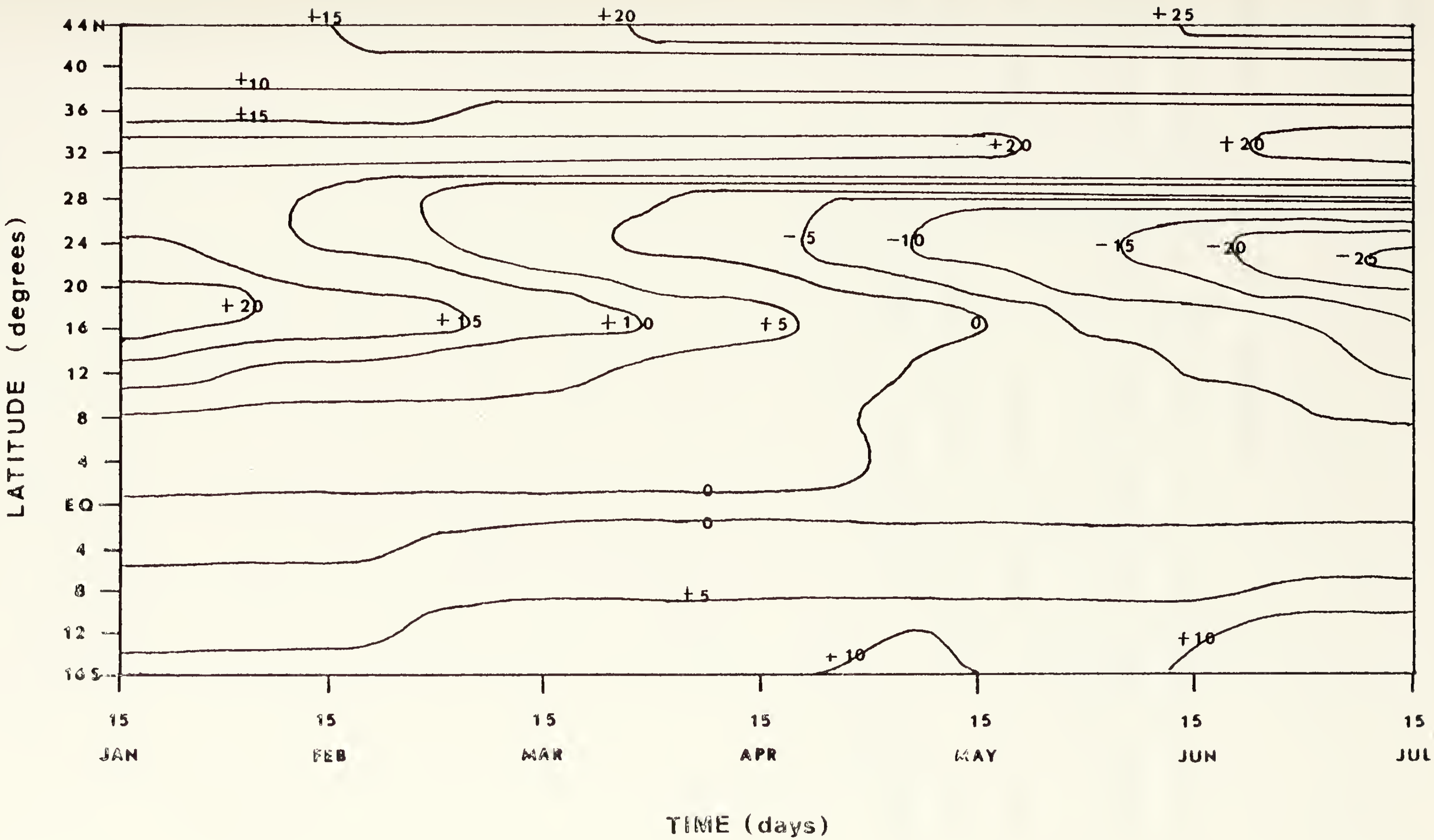

Figure 14: Latitude-time section of zonal wind (m sec^{-1}) for the topography experiment.

Because of the early arrival of the easterly jet in both experiments, the simulated timing of the monsoon development is very poor, with the no-topography case being, paradoxically, the better of the two, however.

The gradual acceleration of the zonal winds for both cases is apparently related to the specified linear change of the equilibrium temperatures. In the real atmosphere, the temperature change, i.e., the reversal of north-south temperature gradient, occurs rather suddenly in mid-May, so that the simulation of the change in temperature is unrealistic and it causes the gradual reversal of the zonal flow.

IV. DISCUSSION

The results of the two experiments indicate that the simplifications used in the numerical model are unrealistic. These simplifications can be broken into two general areas, one related to the model itself and a second related to the data used.

A. MODEL SIMPLIFICATIONS

For both experiments, a zonal symmetry assumption was imposed. It appears that an exclusion of zonally asymmetric eddy motions may lead to an unacceptable circulation pattern, due to the importance of nonlinear processes, as shown by Krishnamurti [1971] and others. A more severe problem of the model is perhaps the vertical resolution, as evident by the extremely poor simulation of the time evolution of the 250 mb zonal flow in the topography experiment. Only three levels in the troposphere are apparently insufficient because of the steepness of the Himalaya mountains. As a result, the interpolation of the simulated data from sigma levels to constant pressure surfaces suffers from the crude vertical resolution.

B. DATA SIMPLIFICATIONS

Clearly shown in the model results, the zonal velocity is underestimated in January for both the topography and no-topography experiment, although the July velocities are in somewhat better agreement with observation. As stated

previously, the July equilibrium temperature specified in the model has been modified from the mean by observations of Krishnamurti [1971]. No similar modification was made in January as only the zonal mean temperatures are used. Because the wind is quite geostrophic and is coupled with temperature gradient through the thermal wind equation, an error in temperature will precipitate an error in winds. It is therefore necessary to improve the specification of the thermal field for January.

The specification of seasonal temperature changes by the linear interpolation between January and July produces the obvious and unrealistic gradual and almost linear wind changes. It appears necessary that the time series of the actual temperature data must be used to adjust the thermal state of the model atmosphere.

Only when this realistic temperature change and an adequate vertical resolution are used in the model can the mechanical effect of the mountains on the zonally symmetric circulation be adequately studied.

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